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Sediment carbon concentration and transport from small watersheds under various conservation tillage practices

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Abstract

Carbon sequestration by soils is viewed as a process that can reduce CO_2 emission and its potential impacts on global climate change. Therefore, impacts of various agricultural management practices on carbon (C) release/sequestration need to be assessed. The objective of this study was to measure C concentrations and transport in sediments lost with various tillage practices on small watersheds. Corn–soybean/rye (*Zea mays* L.–*Glycine max* (L.) Merr./*Secale cereale* L.) rotations with no-till, chisel-plow, and paraplow were studied on small watersheds (0.55–0.79 ha). Disk tillage preceding the corn and soybean crops of a corn–soybean–wheat (*Triticum aestivum* L.)/clover (*Trifolium pratense* L.) rotation was also studied. Each small watershed was instrumented with a 60 cm H-flume mounted on a concrete approach, and a Coshocton wheel for collecting a proportional sample of water and sediment. Samples of sediment deposited in the flume approach and in runoff were collected during a 15-year period and analyzed for total C concentration. Weighted averages of C in the sediment that passed through the flumes during the treatment periods did not differ significantly among tillage treatments, although no-till had the highest C (30 g kg^{-1}) and disk had the lowest C (23 g kg^{-1}) in the last 9 years of the study period. Weighted averages of C concentration in the flume floor sediments were slightly lower (21–23 g kg^{-1}). For comparison, weighted C concentration in sediment that passed through flumes from small fertilized, pastured watersheds ranged from 52 to 72 g kg^{-1}. Average annual sediment loss was 532, 828, and 1152 kg ha^{-1} for no-till, chisel-plow, and disk, respectively. Annual average transport of C via sediment was 13.8, 15.0, 12.7, and 24.0 kg ha^{-1} for no-till, chisel-plow, paraplow, and disk, respectively. Although tillage practices may reduce C transport in sediment by lowering concentrations, a greater factor for reducing C movement is reducing sediment movement. This information will be useful to policy makers and others who need to put definitive values on land management practices in terms of C sequestration/release.
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Keywords: Sediment carbon; Carbon transport; Carbon sequestration; Erosion; Sediment loss; Conservation tillage

1. Introduction

Organic matter has long been recognized as a component of "good" soil, and one of the factors for maintaining or increasing soil health is to maintain or increase soil organic matter (Doran et al., 1996).

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But global climate change as a result of greenhouse gas emission, such as CO_2, has brought a new emphasis and a new perspective to the importance of soil organic matter and soil C. Not only does increasing soil organic matter improve soil properties but it impacts the global C budget through sequestration of atmospheric C in soil (Doran et al., 1998). The amount of soil C sequestered, released, transported, etc. varies with land use and cultural practice (Lal et al., 1995, 1997). Changing management practices to sequester more soil C has been receiving attention at international policy/treaty levels.

There is wide acceptance that cultivating native land, either prairie or forest, causes loss of soil organic matter. Davidson and Ackerman (1993) reported 20–40% loss of soil organic matter following the conversion of previously untilled soils to agricultural production. After 70 years of cultivation, organic C decreased by 36% in the soil profile at the midslope position in a native prairie catena (Voroney et al., 1981). Changes in agricultural practices are reversing this trend (Buyanovsky and Wagner, 1998). Romkens et al. (1999) found that conversion of arable land in the Netherlands to pasture caused regeneration of the soil C content. Conversion of land from plow tillage to long-term no-tillage management often increases soil organic C and N content (Doran, 1980, 1987; McCarty et al., 1995; McCarty and Meisinger, 1997). McCarty et al. (1998) found stratification of organic matter in the soil profile characteristic of long-term no-till soils to progress rapidly within 3 years after conversion to no-till management, although ‘‘evidence was equivocal for any significant increase in organic matter content’’. However, in the Rolling Pampa of Argentina, Alvarez et al. (1998) found a negative annual C budget under no-tillage and plow tillage systems. They concluded that no-tillage would not significantly affect soil organic matter pools in regions with low erosion losses.

Among the multiple pathways of C loss from agricultural fields is C lost with sediment. Assessment of C losses have frequently been part of nutrient loss studies in surface runoff from plots (Massey and Jackson, 1952; Wan and El-Swaify, 1997; Zobisch et al., 1995), or part of erosion plots studies (Ambassa-Kiki and Nill, 1999; Kaihura et al., 1999). Sediments enriched with organic C compared with surface soil have been observed for a variety of soils—from silt loam soils in Wisconsin (Massey and Jackson, 1952) to clay soils in Hawaii (Wan and El-Swaify, 1997). In a review of literature about C redistribution and loss by erosion, Gregorich et al. (1998) concluded that erosion usually resulted in decreased primary production and that the quantity of soil organic C decreased because of a reduction in primary production. They stated two main ways that the physical processes of erosion and deposition impact soil C distribution. First, these processes ‘‘drastically alter the biological process of C mineralization in soil landscapes’’. The second way is the redistribution of soil C ‘‘within a toposequence or a field, or to a distant site’’. The focus of this paper is dealing with the latter.

Many of the studies of C loss from cropped fields do not address sediment C or are plot studies which have C as a part of a group of nutrients instead of the central focus. Also, previous work has not included a perspective on the potential impacts of sediment/C control practices on global C issues. Therefore, the objectives of this research were to: (a) measure the C concentration in sediment leaving small watersheds (field edge) in a corn–soybean rotation (or corn–soybean–wheat/clover rotation) under various conservation tillage practices, (b) determine the amounts of C transported in the sediments from these watersheds, and (c) use the information in (a) and (b) to determine whether total C losses from a field via sediment transport could be reduced by the selection of a conservation tillage practice. Such information will be useful in global C trading decisions as to whether or to what extent conservation tillage practices could be used to keep sequestered soil C in the field.

2. Material and methods

This study was conducted at the North Appalachian Experimental Watershed near Coshocton, OH. Six watersheds, each <0.8 ha (Table 1), were managed in a 2-year corn–soybean/rye rotation beginning in 1984. Rye was a winter cover crop. Two of the watersheds were chiseled each spring to 25 cm depth at 30 cm spacing (Table 2). Two other watersheds were paraplowed each fall to approximately 35 cm at 50 cm spacing. The remaining two watersheds received no-tillage (Edwards et al., 1993). In 1990, the two paraplowed watersheds along with a seventh watershed

Table 1
Tillage treatments and selected landscape and soil characteristics of the six watersheds (Shipitalo and Edwards, 1998)

Watershed No.	Tillage	Area (ha)	Average slope (%)	Maximum length (m)	Shape	Dominant soil[a]
WS 113	No-till	0.59	11	118	Triangular	Coshocton SiL
WS 118	No-till	0.79	10	132	Triangular	Coshocton SiL
WS 109	Chisel-plow	0.68	13	110	Pentagonal	Rayne SiL
WS 123	Chisel-plow	0.55	7	107	Fan	Keene SiL
WS 115	Paraplow/disk	0.65	7	119	Triangular	Coshocton SiL
WS 127	Paraplow/disk	0.68	9	104	Fan	Coshocton SiL

[a] Rayne: fine-loamy, mixed, mesic Typic Hapludult; Keene: fine-silty, mixed, mesic Aquic Hapludalf; Coshocton: fine-loamy, mixed, mesic Aquultic Hapludalf; SiL: silt loam.

were placed in a 3-year, reduced chemical input rotation (corn–soybean–wheat/clover) (Shipitalo and Edwards, 1998). Wheat was harvested for grain, and clover was disked prior to corn planting. Three watersheds in this rotation made it possible to have a watershed in each stage of the rotation each year. To achieve this in the corn–soybean rotation watersheds, cropping was changed in the 7th year to have one watershed in each tillage practice in each crop every year (Table 2).

Soils were formed in residuum and colluvium derived from underlying sandstone and shale bedrock. The dominant soil types are Coshocton silt loam (fine-loamy, mixed, mesic Aquultic Hapludalf), Keene silt loam (fine-loamy, mixed, mesic Aquic Hapludalf), and Rayne silt loam (fine-loamy, mixed, mesic Typic

Table 2
Tillage and cropping management for the conservation tillage watersheds (annual cycle was May through April)

Year	No-till		Chisel-plow		Paraplow	
	WS 113	WS 118	WS 109	WS 123	WS 115	WS 127
First 6 years of the study period						
1984	Corn	Corn	Corn	Corn	Corn	Corn
1985	SB/R[a]	SB/R	SB/R	SB/R	SB/R	SB/R
1986	Corn	Corn	Corn	Corn	Corn	Corn
1987	SB/R	SB/R	SB/R	SB/R	SB/R	SB/R
1988	Corn	Corn	Corn	Corn	Corn	Corn
1989	SB/R	SB/R	SB/R	SB/R	SB/R	SB/R
Year	No-till		Chisel-plow		Disk[b]	
	WS 113	WS 118	WS 109	WS 123	WS 115	WS 127
Last 9 years of the study period						
1990	Corn	SB/R	Corn	SB/R	SB	Wh/Cl[c]
1991	SB/R	Corn	SB/R	Corn	Wh/Cl	Corn
1992	Corn	SB/R	Corn	SB/R	Corn	SB
1993	SB/R	Corn	SB/R	Corn	SB	Wh/Cl
1994	Corn	SB/R	Corn	SB/R	Wh/Cl	Corn
1995	SB/R	Corn	SB/R	Corn	Corn	SB
1996	Corn	SB/R	Corn	SB/R	SB	Wh/Cl
1997	SB/R	Corn	SB/R	Corn	Wh/Cl	Corn
1998	Corn	SB/R	Corn	SB/R	Corn	SB

[a] SB/R: Soybean followed with a rye winter cover crop.
[b] Reduced chemical input.
[c] Wh/Cl: winter wheat over-seeded with clover.

Hapludult) (Table 1). The B horizon of the Rayne series contains less clay than the B horizons of the Coshocton or Keene series. Therefore, the Rayne has better internal drainage. Greater details on the soils, geology, and geomorphology of these watersheds were described by Edwards et al. (1993) and Kelley et al. (1975).

Corn was planted with a row spacing of 76 cm and soybean was drilled with a row spacing of 18 cm, approximately on the contour for both crops. Recommended residual corn and soybean herbicides were applied each year for weed control in the corn–soybean/rye rotation. Rye, used as a winter cover crop following each soybean year, was killed the following spring with a contact herbicide. Herbicides were applied at one-half of the recommended rates on the reduced-input watersheds when planted to corn and herbicide was applied only to a band over the row when soybean was planted. The corn and soybean crops in the reduced-input watersheds were cultivated for additional weed control twice during the growing season. Wheat was drilled into the reduced-input watersheds following soybean harvest in October, and it also served as a winter cover crop instead of rye. Red clover was broadcast seeded into the standing wheat in March or April. Further details on operations and fertility management were presented by Edwards et al. (1993) and Shipitalo and Edwards (1998).

Surface runoff from the watersheds was automatically measured with 0.60 m H-flumes and sampled with Coshocton wheels (Brakensiek et al., 1979) modified to continuously deliver a proportional sample of runoff water and suspended sediment to a refrigerated container during each runoff event. Separate samples were usually collected for each runoff event unless storms occurred less than a few hours apart.

Soil losses were determined by filtering the runoff samples to ascertain sediment concentrations and multiplying by the runoff volumes calculated from the hydrographs. Sediment was occasionally deposited in the flume and flume approach. This sediment was collected and weighed. Five soil samples were collected in each watershed each spring. Samples were taken to a depth of 30 cm with a 2.5 cm diameter sampler that was driven into the soil by stepping on the top. All samples were air dried and stored. Each sample was taken near a soil moisture tube in watersheds so that a similar area was sampled each year. Because of the expense of analyzing all the samples and because C concentrations changed little with a 1-year interval, samples from selected years during the study period were analyzed.

Total C on sediment was analyzed by the dry-combustion method using a model PE2400 Series II CHN analyzer (Perkin-Elmer). Carbon concentrations were multiplied by sediment quantities to calculate C transported. Weighted average C concentrations were calculated by dividing the total C transported during a given time period by the total sediment transported during the same time period. Even though sediment quantities were determined for all runoff events, not all events produced sufficient sediment for analysis. For these events, C transport was estimated by using an estimated C concentration from a recently occurring event. Even though C concentration for approximately 50% of the sediment was estimated, the accuracy for the amount of total C transported via sediment was little impacted because sediment C concentrations varied little. Statistically, significant differences were determined by General Linear Model procedures (SAS, 1985).

3. Results and discussion

3.1. Carbon concentration on sediment

Although sediment losses occurred almost every year from each watershed, there was sufficient sediment for C analyses in less than half of the watershed-years (Table 3). Therefore, C comparisons were made with less than 15 years of sediment C concentration data from this study.

Average C concentration on sediments passing through the H-flume (wheel sediment) usually did not differ significantly among crops in the rotations (Table 3). Although sediment C concentration from years in soybeans was usually lower than from years in corn, this difference was significant only in the no-till fields. For the entire 15-year period, the weighted average of C concentration in sediment under no-till was significantly greater than the C concentration in sediments from the other tillage practices. With time, the sediment C concentration was reasonably stable with the no-till practice and appeared to increase with

Table 3
Weighted average C concentration (g kg^{-1}) on sediments passing through the H-flume and collected with the Coshocton wheel; annual cycle was May through April (number of events during that year)[a]

	No-till		Chisel-plow		Paraplow/disk	
	WS 113	WS 118	WS 109	WS 123	WS 115	WS 127
1984–1985	NA[b]	NA	NA	NA	NA	NA
1985–1986	NA	NA	14.5 (1)	NA	18.5 (1)	13.0 (1)
1986–1987	27.6 (1)	NA	15.7 (2)	18.5 (2)	18.9 (1)	NA
1987–1988	NA	25.2 (6)	24.3 (4)	NA	21.0 (1)	24.2 (2)
1988–1989	NA	NA	NA	24.3 (1)	NA	NA
1989–1990	NA	20.2 (2)	14.2 (5)	NA	NA	21.2 (2)
1990–1991	33.9 (1)	26.7 (2)	15.2 (11)	19.6 (1)	15.2 (9)	NA
1991–1992	NA	31.3 (3)	NA	NA	NA	NA
1992–1993	NA	24.0 (10)	NA	NA	NA	26.8 (3)
1993–1994	23.8 (1)	24.3 (3)	25.7 (2)	24.8 (3)	23.3 (3)	NA
1994–1995	NA	23.2 (2)	NA	NA	NA	NA
1995–1996	27.9 (4)	32.0 (1)	22.5 (1)	29.3 (1)	23.3 (1)	24.0 (10)
1996–1997	26.6 (2)	NA	NA	16.9 (2)	25.9 (2)	29.0 (2)
1997–1998	18.3 (2)	NA	24.3 (2)	NA	NA	21.2 (2)
1998–1999	NA	NA	NA	NA	NA	NA
Tillage means						
Corn years	29.6 a		21.3 a		21.1 a	
Soybean years	24.1 b		20.2 a		21.3 a	
Wh/Cl years	NA		NA		29.0 b	
Over all[c]	26.1 x		20.7 y		21.8 y	

[a] Means within a column followed by the same letter are not significantly different at the 0.05 level.
[b] Not available.
[c] Means in this row followed by the same letter are not significantly different at the 0.05 level.

the other tillage practices. However, the variability was too great for apparent trends to be significant. For comparison, weighted C concentration averages in sediment that passed through H-flumes from small fertilized, pastured watersheds ranged from 52 to 72 g kg^{-1}. These C values were from 27 samples collected from 1975 to 1998 from multiple pasture treatments. The majority of these pasture sediments came from an area used for both summer grazing and winter feeding.

Watershed management history prior to the conservation tillage study (Table 4) probably was a major factor in the differences in C concentration on the sediments in the first years. In an effort to have some uniformity in watershed soil conditions prior to the start of the conservation tillage comparisons, the first six watersheds were each sown to wheat with clover. They were then fall moldboard plowed and planted to rye. At this time there were no C objectives, and soil C concentrations were not considered in determining which tillage practice was assigned to a particular watershed.

The no-till watersheds were in meadow for the 7 years prior to the wheat–clover–rye (WCR) year (Table 4). The chisel-plow and paraplow had only 2 or 3 years of meadow in the prior 10 years, and there were 5 or 6 years of corn between the meadow years and the WCR year. Although soils with no-till corn can have higher C concentrations than corn grown on tilled soils, grasslands can have even higher C levels. Owens and Hothem (2000) found 1.6 to 2.3 times (19–28 g kg^{-1} C) greater C in the 0–15 cm soil layer of various pasture systems than in soil under a no-till corn–soybean/rye rotation (12 g kg^{-1}). Soil organic C of the surface 5 cm of soil was 50% greater under long-term pasture than under long-term no-tillage in Georgia (Franluebbers et al., 2000). Thus, the sediments coming from the no-till watersheds would be expected to have higher C concentration in the early years than the other watersheds. Another factor was

Table 4
Watershed tillage and cropping management prior to the current 15-year conservation tillage study

Year	No-till		Chisel-plow		Paraplow	
	WS 113	WS 118	WS 109	WS 123	WS 115	WS 127
1973	NT corn[a]	Corn	Corn	NT corn	NT corn	NT corn
1974	NT corn	NT corn	Corn	NT corn	NT corn	NT corn
1975	NT corn	Corn	Meadow	Meadow	Meadow	Meadow
1976	Meadow[b]	Meadow	Meadow	Meadow	Meadow	Meadow
1977	Meadow	Meadow	NT corn	Meadow	Meadow	Meadow
1978	Meadow	Meadow	NT corn	Corn	NT corn	NT corn
1979	Meadow	Meadow	NT corn	Corn	NT corn	NT corn
1980	Meadow	Meadow	NT corn	Corn	NT corn	NT corn
1981	Meadow	Meadow	NT corn	Corn	NT corn	NT corn
1982	Meadow	Meadow	NT corn	Corn	NT corn	NT corn
1983	WCR[c]	WCR	WCR	WCR	WCR	WCR

[a] Corn grown with no-tillage.
[b] Ungrazed grassland.
[c] Wheat planted with clover, fall moldboard plow, then planted to rye.

that no sediment C concentration data were obtained from the no-till watersheds until the 3rd and 4th years (Table 3). Therefore, there were a few years during which the decaying surface residue could have increased the soil C of the surface soil before a sediment C concentration was determined.

Approximately 18% of the total sediment leaving the watersheds was deposited in the flume floor and flume approach. The weighted average C concentration in these sediments was 22 and 23 g kg^{-1} for the no-till watersheds and 16 and 18 g kg^{-1} for the chisel-plow watersheds. Wheel sediments were enriched with C compared with flume floor sediments, respectively. This was probably a result of particle size and density differences among soil constituents, in which coarser mineral sediment particles settled in the flume while lighter organic particles passed through the wheel.

Not only were wheel sediments enriched in C concentration compared with flume floor sediments but they were also enriched compared with the surface soil. The enrichment ratio (ER) for sediments from the no-till and chisel-plow watersheds to the 0–2.5 cm soil layer was 1.5 (Table 5). The ER variability was greater from the chisel-plow watersheds than from the no-till watersheds. The lowest ER occurred in 1999 from a disk watershed and resulted from low C concentration in sediments. In the disked watersheds, rills developed

Table 5
Ratio of average C concentration on sediment to average C concentration in the 0–2.5 cm soil layer

Year	No-till		Chisel-plow		Paraplow/disk	
	WS 113	WS 118	WS 109	WS 123	WS 115	WS 127
1985	1.8[a]	1.5	1.5[a]	1.4	1.4	1.4
1986	1.8	1.4	0.9	1.2	1.4	1.0
1988	1.4	1.4	1.6	1.1	1.1	1.4
1990	1.3	1.9	0.9	1.7	0.9	1.1
1995	1.7	1.4	2.3[a]	1.7	1.2[a,b]	1.5[b]
1999	1.3	1.4	1.8	1.9	0.6[b]	1.0[b]
Mean + S.D.	1.5 ± 0.2		1.5 ± 0.4		1.2 ± 0.3	

[a] Annual sediment <10 kg ha^{-1}.
[b] Disk.

Table 6
Average annual wheel and total (wheel plus flume floor) sediment and C transport by crop and tillage practice

Management	Wheel sediment (kg ha^{-1})		Total sediment (kg ha^{-1})	
	Sediment	C	Sediment	C
No-till (15 years)				
Corn	236 ± 245	6.9 ± 7.2	262 ± 271	7.5 ± 7.8
Soybean	682 ± 789	17.4 ± 19.0	800 ± 850	20.0 ± 20.2
Over all	459 ± 617	12.1 ± 15.1	531 ± 686	13.8 ± 16.6
Chisel-plow (15 years)				
Corn	974 ± 2141	17.4 ± 34.0	1258 ± 2954	22.0 ± 46.6
Soybean	356 ± 584	7.2 ± 10.1	399 ± 640	8.0 ± 11.2
Over all	665 ± 1573	12.3 ± 25.2	828 ± 2180	15.0 ± 34.6
Paraplow (6 years)				
Corn	273 ± 416	5.5 ± 8.4	317 ± 463	6.4 ± 9.2
Soybean	737 ± 830	16.3 ± 21.0	883 ± 937	19.1 ± 23.0
Over all	505 ± 672	10.9 ± 16.2	600 ± 791	12.7 ± 18.7
Disk (9 years)				
Corn	302 ± 444	6.8 ± 9.7	348 ± 539	7.8 ± 11.8
Soybean	2193 ± 2043	43.9 ± 36.2	2956 ± 2778	60.1 ± 49.6
Wh/Cl	127 ± 128	3.5 ± 3.7	151 ± 151	4.1 ± 4.3
Over all	874 ± 1529	18.1 ± 28.4	1152 ± 2076	24.0 ± 39.0

and allowed some erosion to occur from soil depths greater than 2.5 cm, where the C concentrations were lower. Thus, the overall C concentration in the sediments was probably lower than if the sediments had come only from the 0–2.5 cm layer.

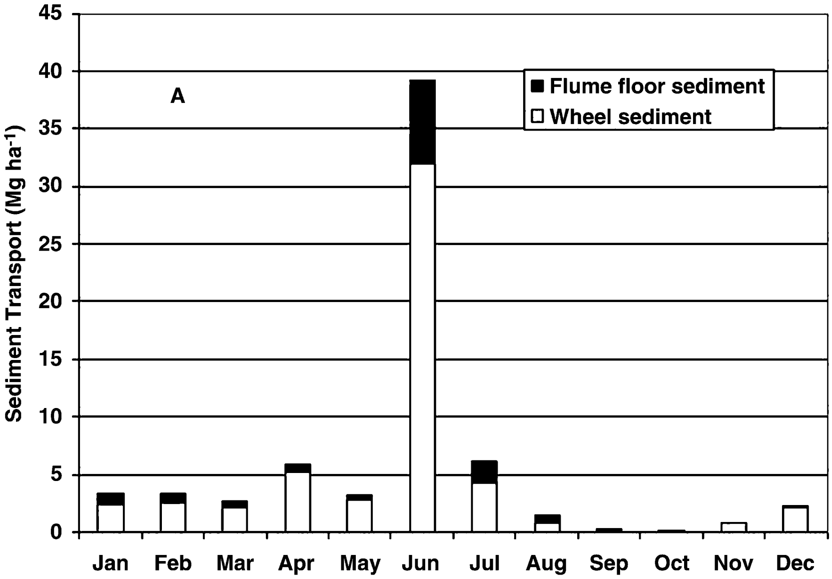
3.2. Carbon transported via sediments

Although differences and trends in sediment transport can be noted based on tillage practice or crop year (Table 6), the year to year variation was so great that there were no significant differences among the values reported. The standard deviation was almost always greater than the mean for each practice and year. This was also true for the transport of C in the sediments. Not surprisingly, the lowest annual sediment transport occurred with no-till and the highest with disk. With the exception of the chisel-plow practice, average annual total sediment losses (combined wheel and flume floor sediment) were 2.8–8.5 times greater with soybean than with corn. Sediment total C transport had similar ratios (2.7–7.7 times).

The 1990–1991 year was a record high for precipitation, and major runoff events occurred during June and July. Large amounts of sediment were transported in those events. Approximately 35% of the sediment lost (both flume floor and wheel sediment) during the 15-year study period occurred during the 1990–1991 year. The average amount of sediment transported from each of the watersheds that year was 3979 kg ha^{-1}. During the other 14 years, average annual soil loss ranged from 55 to 1882 kg ha^{-1}. Wide variations in annual C transport also occurred. In the 1990–1991 year, an average of 70 kg ha^{-1} of C was transported from each watershed, and the average annual loss for the other years ranged from 1.1 to 42 kg ha^{-1}.

The large events in June 1990 gave a monthly average sediment transport and carbon transport much greater than any other month (Fig. 1A and B, respectively). In spite of the large monthly differences, there were no significant differences among monthly averages because of the great variability in event sizes and occurrences. A few large events usually transport most of the sediment (Edwards and Owens, 1991).

The monthly distribution of C transport closely followed the pattern of sediment transport because the monthly C concentrations did not vary greatly. During the October through May period, C concentrations on the wheel sediments ranged from 26 to 29 g kg^{-1}; C concentrations were lower during the



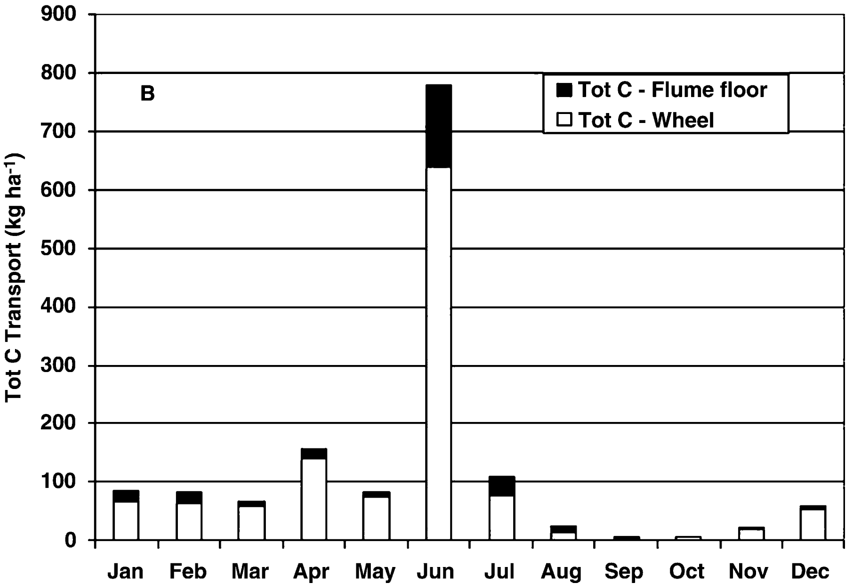


Fig. 1. Monthly average sediment transport (A) and total C transport (B) from all the watersheds during the 15-year study period, May 1984 through April 1999. (In spite of the transport differences among months, variability within the same month across years was so great that there are no significant differences.)

June through September period (17–21 g kg^{-1}). Monthly C concentrations on the flume floor sediments were slightly lower than on the wheel sediments, but followed a similar pattern (21–23 g kg^{-1} for December through May and 15–19 g $kg^{-1}$for June through November).

4. Conclusions

Carbon concentrations on sediment lost from watersheds with different tillage practices (e.g. no-till, chisel-plow, paraplow, and disk) varied little with time. Tillage practices and weather had major impacts on soil loss from field scale watersheds; however, they had much less impact on sediment C concentration. Management systems that control sediment loss have a greater impact on reducing C loss via erosion than those that might change sediment C concentration. Zobisch et al. (1995) made similar conclusions for plot studies. This is relevant to corporate and government policy makers who are dealing with trading C credits, placing a value on soil C, and deciding which soil management practices should be recommended for net storage of C.

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